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1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	March 25, 1994	Reprint

4. TITLE AND SUBTITLE Potential Threat of Solar Proton Events to Missions in Space	5. FUNDING NUMBERS PE 61102F PR 2311 TA G4 WU 01
6. AUTHOR(S) M.A. Shea, D.F. Smart	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Phillips Lab/GPSG 29 Randolph Road Hanscom AFB, MA 01731-3010	8. PERFORMING ORGANIZATION REPORT NUMBER PL-TR-94-2075
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSORING/MONITORING AGENCY REPORT NUMBER

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11. SUPPLEMENTARY NOTES

Reprint from Proceedings of the Topical Meeting on New Horizons in Radiation Protection and Shielding, American Nuclear Society, Inc., LaGrange Park, Illinois 220-230, 1992

12a. DISTRIBUTION/AVAILABILITY STATEMENT	12b. DISTRIBUTION CODE
Approved for public release; Distribution unlimited	

13. ABSTRACT (Maximum 200 words)

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14. SUBJECT TERMS	15. NUMBER OF PAGES
Solar Protons, Cosmic rays, Spacecraft, Magnetosphere, Space hazards, Interplanetary medium	11
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR

Reprint from *Proceedings of the Topical Meeting on New Horizons in Radiation Protection and Shielding*, American Nuclear Socity, Inc., La Grange Park, Illinois, 220-230, 1992.

POTENTIAL THREAT OF SOLAR PROTON EVENTS TO MISSIONS IN SPACE

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ABSTRACT

The flux of solar protons impacting on spacecraft is a function of the location and orbit of the vehicle. Solar proton events will not adversely affect low inclination low altitude orbits and will only moderately impact a polar orbiting vehicle. However, lunar and interplanetary missions may be seriously impacted by a very large flux of energetic solar protons. A summary of our knowledge of solar proton events as acquired over the past half century is presented together with a description of the potential threat of solar protons on various spacecraft orbits both within and beyond the magnetosphere.

CONTENTS

I. INTRODUCTION

Major solar flares are often associated with the acceleration of energetic particles at the sun and their injection into the interplanetary medium where the particles can be detected by a variety of techniques. Only high energy particles could be detected at the earth prior to the space age since only very energetic particles could penetrate the atmosphere to balloon altitudes, or in rare cases, to ground-level detectors. Since the advent of the space era, data obtained from particle sensors flown on spacecraft throughout the heliosphere as well as improved balloon and ground-based instrumentation have greatly increased our understanding of solar particles and their propagation in the solar system.

The amount of solar proton flux impinging upon space vehicles is highly dependent upon the location and orbit of the spacecraft. For low altitude, low inclination orbits similar to those of the space shuttle or the planned space station, the solar proton flux will be considerably attenuated by the shielding effects of the earth's magnetic field; for polar orbiting spacecraft the solar proton flux will be attenuated when the spacecraft is at mid and low latitudes; however, in the polar regions the flux will be essentially equivalent to that in the interplanetary medium. For lunar and interplanetary missions, the spacecraft will be exposed to the entire flux of the solar particle event at that particular location in space. This paper summarizes our knowledge of solar proton events and considers the potential threat of these events to various missions in space.

II. SOLAR PROTON ACCELERATION AND PROPAGATION CONCEPTS

A. Solar Proton Sources

Solar protons are accelerated and released from the sun primarily during solar flares. During the flare process, electromagnetic radiation, including X-ray and radio emission, is generated by the hot plasma and travels to the earth at the speed of light (approximately 8 minutes). The visual observation of a solar flare, usually in the H-alpha wavelength, is approximately simultaneous with the onset of the solar X-ray emission. The transit of solar energetic particles to a point in space is dependent upon the energy of the particle and the location of the flare on the sun with respect to the detection point. Under idealized circumstances, from well connected

solar flares, relativistic solar protons can reach the orbit of the earth (i.e. one Astronomical Unit) within 10-15 minutes of the onset of the flare; 10 MeV protons take approximately 80 minutes to reach the same distance. X-rays, having no charge or mass, travel rectilinearly; solar protons, being charged particles, spiral along the interplanetary magnetic field lines between the sun and the detection point in space.

When a solar flare occurs there is also an associated release of enhanced solar plasma into the interplanetary medium. Occasionally this dense plasma will propagate far into the heliosphere travelling at speeds of 1-3 days per Astronomical Unit. When these plasmas pass the earth, they can manifest themselves by the occurrence of aurora and geomagnetic disturbances, the magnitude of which are dependent upon the interplanetary plasma and field characteristics at the time of the arrival of the plasma at the earth. These "travelling interplanetary plasma discontinuities" can severely disrupt the ambient particle environment; occasionally, for major solar proton events, the ambient flux can be re-accelerated by interaction with the shock front. In severe cases the solar particle flux can be greatly intensified over a period of a few hours. Figure 1 illustrates the solar particle emissions from the sun to the earth.

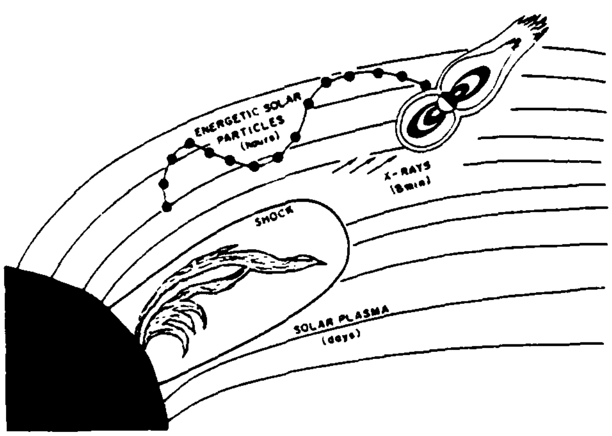

Figure 1. Pictorial representation of energetic particle propagation from the sun to the earth. The relative time scales are noted.

Although the solar flare process is the most commonly assumed source of solar protons, recent research indicates that the coronal mass ejection may be the phenomenon that is associated with the acceleration and release of solar protons into the interplanetary medium. Since most major solar flares are associated with solar mass ejections, it is still customary to refer to solar proton events as emanating from solar flares. However, it should be realized that other phenomena such as disappearing solar filaments and interplanetary magnetic sector boundary crossings, can give rise to increases on the background flux of solar particles; however, these are relatively small perturbations and would not pose a critical threat to spacecraft operations.

B. Solar Proton Event Characteristics

Solar proton events, as measured at the orbit of the earth, have a characteristic intensity-time profile as illustrated in Figure 2. Although the general shape of the intensity-time profile, as shown in Figure 2, will differ from event to event and also with respect to the location of the flare on the sun and the detection point in the heliosphere, particle events can be characterized by the following: a propagation delay between the onset of the solar flare in electromagnetic emission and the onset of the particle increase; a relatively rapid rise in intensity to a maximum value; and a slow decay to the background level. Although actual event profiles can be complicated by multiple particle injections or interplanetary perturbations, this simplified picture is appropriate for any one isolated event.

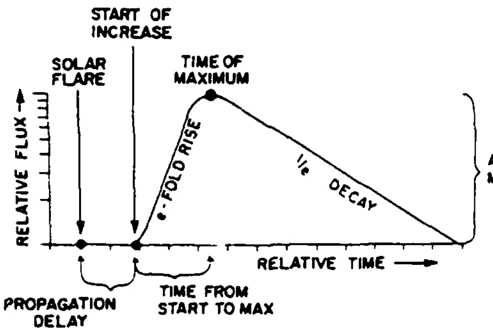

Figure 2. Characteristic profile of the solar particle intensity as a function of time at 1 Astronomical Unit.

C. Solar Proton Propagation

From examining solar proton data acquired since 1955, we can generalize and separate the propagation of solar protons from the solar flare site to a location in space into two distinct and independent phases. The first phase is diffusion from the flare site through the solar corona to the "foot" of the idealized Archimedean spiral path formed by the interplanetary magnetic field line between the sun and the detection point. The maximum possible flux is presumed to be at the solar flare site with a gradient in the solar corona from the flare site. This gradient attenuates the maximum particle intensity as the angular distance from the flare site increases. The second phase is the propagation in the interplanetary medium from the sun to the detection point along the interplanetary magnetic field lines.

If a solar particle producing flare occurs near the "footpoint" of the interplanetary magnetic field line connecting the earth with the sun (which is nominally around 60° west longitude on the sun as viewed from the earth), then a detector located anywhere along this field line (e.g. the earth) should record the earliest onset time and the highest intensity of any detector located at the same radial distance but at different heliolongitudes. If a flare occurs at any other solar longitude, the particles which reach the earth are first transported through the solar corona to the interplanetary field line connecting the sun with the earth whereupon they propagate along the field line to the earth. Figure 3 is an illustration of this propagation concept.

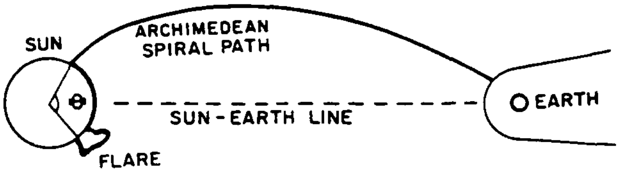

Figure 3. Illustration of the propagation concept. The coronal propagation distance is illustrated by the heavy arc on the sun. Interplanetary propagation proceeds along the interplanetary magnetic field lines which, for a constant speed solar wind, forms an Archimedean spiral path from the sun to the earth.

Figures 4 and 5 illustrate typical intensity-time profiles that would be recorded at one Astronomical Unit from identical solar flare energetic proton sources at different locations on the sun. The intensity-time profile shown on the lower right side of Figure 4 is typical for a flare that occurred at the "footpoint" of the interplanetary magnetic field line connecting the sun with the earth. Notice the rapid rise to maximum intensity. The particle flux would be maximum along the favorable propagation path (shown by the larger dots) whereas particles that diffuse through the solar corona to other field lines would have a smaller flux (shown by smaller dots).

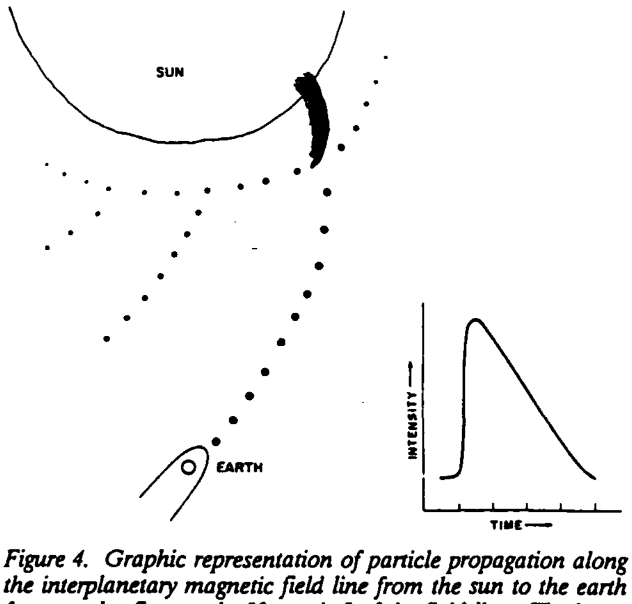

Figure 4. Graphic representation of particle propagation along the interplanetary magnetic field line from the sun to the earth from a solar flare at the "footpoint" of the field line. The larger the dot, the larger the flux. A typical intensity-time profile for this event, as measured at the earth, is shown on the right.

Figure 5 illustrates the particle flux in the inner heliosphere from a flare to the east of the earth-sun line. The left side of this figure shows that the maximum flux (large dots) would be along the interplanetary magnetic field line from the flare location to the hypothetical spacecraft located at one Astronomical Unit. While particles from this flare are propagating along the field line to the satellite, they are also propagating, albeit with a reduced intensity, through the solar corona to other field lines. Those particles which reach the interplanetary field line connecting the earth with the sun have started to propagate along this field line to the earth; however, as seen from the lower section of this portion of the figure the particle intensity at the earth is still at the background level whereas at the spacecraft the maximum intensity has already been measured. The top section of the right side of this figure illustrates the particle intensity in the inner heliosphere a few hours later when both the spacecraft to the left (and a hypothetical spacecraft at the earth) would be responding to an enhanced solar particle flux. The lower section of this portion of the figure shows the intensity-time profiles which would have been recorded by both spacecraft during this event. The spacecraft at the earth would have recorded a later onset time, slower rise time, smaller maximum flux, and longer decay time than the spacecraft located along the field line connected to the flare site.

D. Solar Proton Prediction

A full description of our ability to predict the occurrence and magnitude of solar proton events is beyond the scope of this paper. At the present time it is not possible to predict when a solar proton-producing flare is likely to occur. Even flare prediction is in its infancy. Certain magnetic configurations within the solar active region have proved to be useful parameters for identifying a region that might produce a significant flare; however, there is no unique indicator that the flare will produce copious solar particles.

Solar proton prediction is based on observables such as the location of the flare on the sun, the electromagnetic emission, and the status of the interplanetary medium. The techniques used by the forecast centers are all based on observations made at the earth. Although the general principals would remain the same, additional techniques would have to be developed to predict an intensity-time profile for an interplanetary mission. Smart and Shea [1] summarize our present ability to predict and model the solar proton intensity at the earth after a major solar-proton producing flare.

III. DETECTION OF SOLAR PROTON EVENTS

The detection of solar proton events covers a span of 50 years. Our ability to detect these events started with the operation of cosmic ray muon detectors (i.e. ionization chambers) in 1932. However, it wasn't until 1942 that the first solar proton events were recorded by these detectors which respond to the secondaries generated in the atmosphere from incident solar protons having energies ~ 4 GeV. Since 1953 cosmic ray neutron monitors have been in continuous operation. These sensors, if located at high latitudes, can detect the secondaries generated by protons above approximately 450 MeV. Solar proton events have also been detected by sensors flown on balloons since the International Geophysical Year (1957-1958), and on spacecraft since the early 60's. In addition, the ionosphere responds to an influx of solar protons and is, in itself, a means of detecting the presence of solar particles. Figure 6 illustrates the history of solar proton detection methods. At the present time our most reliable method of identifying solar proton events is by spacecraft measurements.

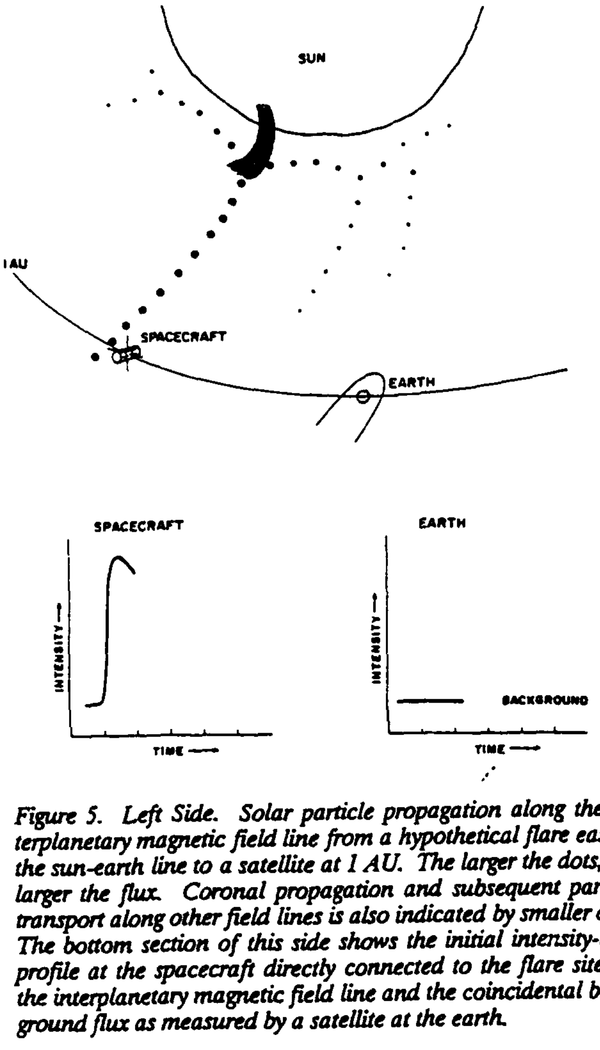

Figure 5. Left Side. Solar particle propagation along the interplanetary magnetic field line from a hypothetical flare east of the sun-earth line to a satellite at 1 AU. The larger the dots, the larger the flux. Coronal propagation and subsequent particle transport along other field lines is also indicated by smaller dots. The bottom section of this side shows the initial intensity-time profile at the spacecraft directly connected to the flare site via the interplanetary magnetic field line and the coincidental background flux as measured by a satellite at the earth.

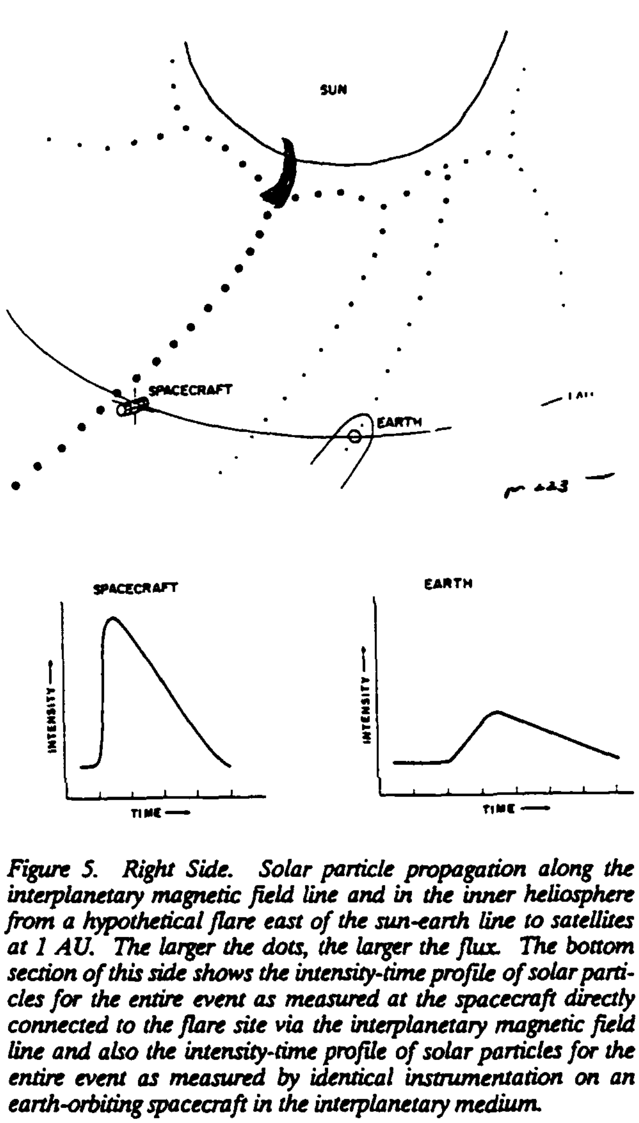

Figure 5. Right Side. Solar particle propagation along the interplanetary magnetic field line and in the inner heliosphere from a hypothetical flare east of the sun-earth line to satellites at 1 AU. The larger the dots, the larger the flux. The bottom section of this side shows the intensity-time profile of solar particles for the entire event as measured at the spacecraft directly connected to the flare site via the interplanetary magnetic field line and also the intensity-time profile of solar particles for the entire event as measured by identical instrumentation on an earth-orbiting spacecraft in the interplanetary medium.

In the sections that follow the terms "flux" and "fluence" will be used. Particle physicists usually refer to the peak flux observed in a specific channel of a solar particle detector. This can be either an integral flux above a specified energy level, in units of particles/ cm^2-sec-ster or a differential measurement which specifies the flux at a specific energy in units of particles/cm^2-sec-ster-MeV. Individual events are usually compared using identical channels. The peak flux specifies the maximum particle flux from which can be derived a corresponding interaction rate. Peak flux is usually used to describe individual solar particle events.

Fluence is the total number of particles above a selected energy that is experienced throughout an entire event. Fluence may be given in either directional units of particles/cm^2-ster or omni-directional units of particles/cm^2. The fluence is generally of concern for the total radiation exposure.

A. Identification of "Significant" Solar Proton Events

Continuous geophysical monitoring was advocated as essential for the success of the International Geophysical Year with the result that fairly consistent ground-based measurements were acquired and the data archived for future use. However, prior to the space era it was difficult to determine the flux of solar protons from the ground-based measurements. Once space measurements became routine, simultaneous satellite and ground-based observations were examined in an effort to determine the magnitude and effect of solar protons on the geophysical environment. For example, an excellent relationship was found between polar riometer measurements and peak solar proton flux above 10 MeV. From studies such as these it became possible to extend the solar proton data base backward in time to the 19th solar cycle (1954-1965).

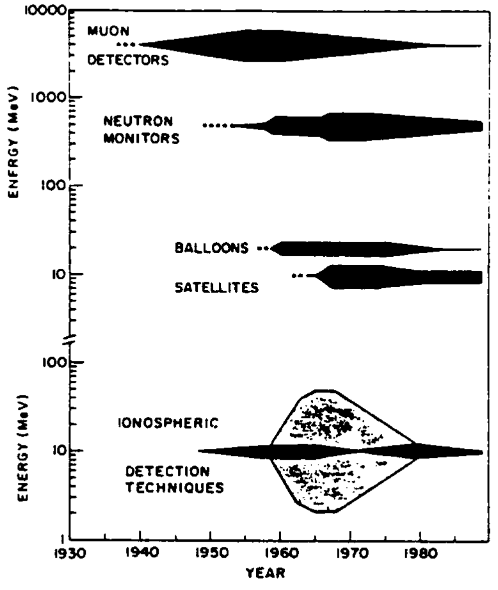

Figure 6. Conceptual history of the detection thresholds of solar proton events. The thickness of the lines indicates the relative number of each type of detector in use. The differences in shading in the ionospheric section indicates changes in detection techniques.

Using the various data sets that extend over the past three solar cycles (1954-1986), Shea and Smart [2] identified 218 "significant" solar proton events at the earth. Their criterion of a 10 MeV proton flux greater than 10 protons/cm^2-sec-ster is the presently accepted value for identification of a proton event that has the potential of producing perturbations to the geophysical environment. In a statistical study of these events using the sunspot number as a measure of the solar cycle, these scientists found that although the number of proton events increased during the years of maximum sunspot number, there was no predictable pattern from one solar cycle to the next. Figure 7 shows the number of discrete solar proton events (shown as individual dots) for each 12-month period after solar minimum and the 12-month mean sunspot number for the corresponding period (histogram) for each of the past three solar cycles. The number of proton events per year (i.e. 12-month period) vs. the 12-month mean sunspot number for the corresponding period, is given in the lower right [3].

When combining these data into one set for the three solar cycles, we [4] derive the distribution shown in Figure 8. The data, organized in 12-month periods beginning with the month after sunspot minimum as defined by the statistically smoothed sunspot number, indicates that these proton events occur primarily from the 2nd through the 8th year of the solar cycle. For unexplained reasons, there is also an increase in the 10th year of each of the three solar cycles which combine to give an increase in events for year 10.

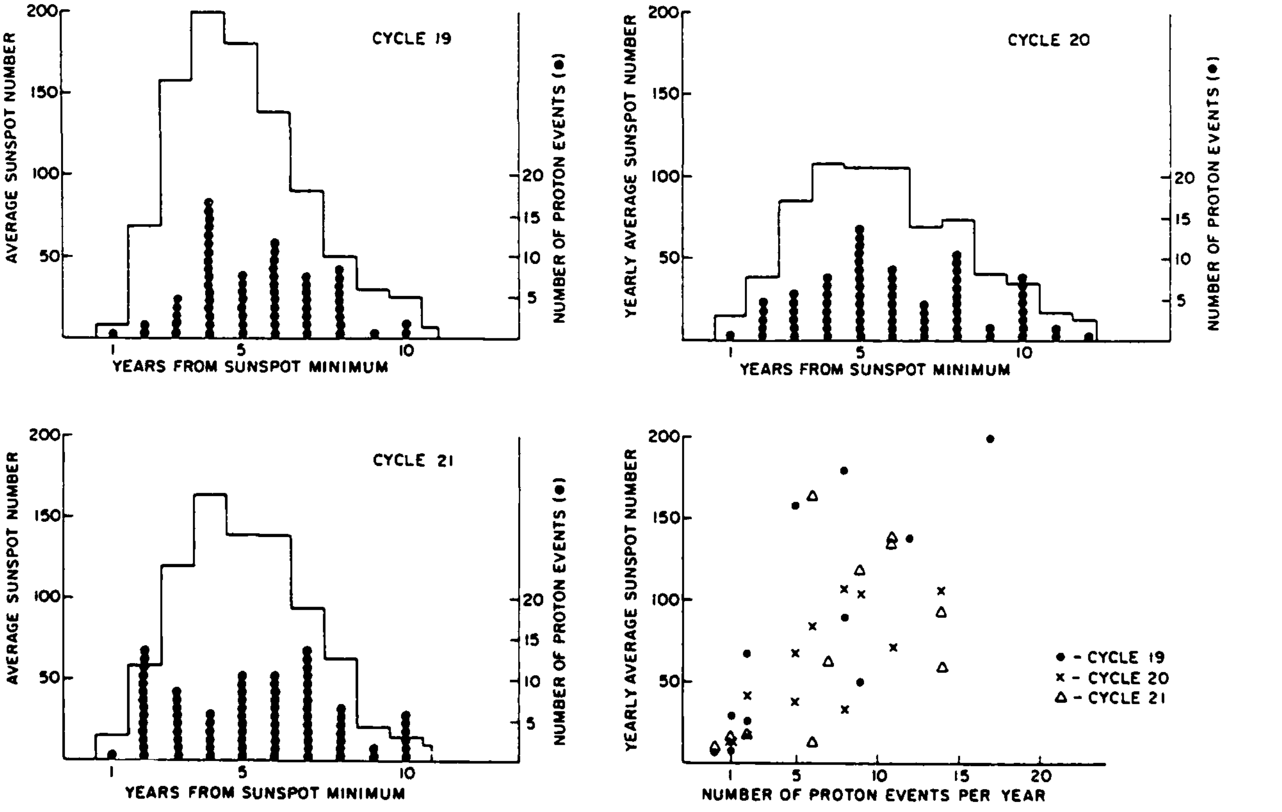

Figure 7. Number of solar proton events (dots) for each 12-month period after solar minimum and the 12-month mean sunspot number of the corresponding period (histogram) for each of the past three solar cycles.

Figure 7. (continued) Lower right: The number of proton events per year (i.e. 12-month period) vs. 12-month mean sunspot number for the corresponding period. The values for each solar cycle are separately identified.

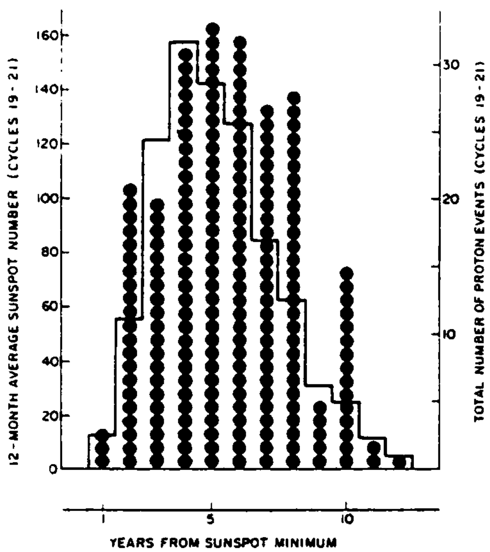

Figure 8. Summation of discrete solar proton events (shown as solid dots) for solar cycles 19-21 and the corresponding 12-month average sunspot number (histogram). The data are organized in 12-month periods beginning with the month after sunspot minimum as defined by the statistically smoothed sunspot number.

B. Episodes of Activity

In compiling the list of significant proton events over the past three solar cycles, Shea and Smart [2] found occasions where one active region passing across the solar disk produced many major solar flares several of which released particles associated with the aggregate particle event observed at the earth. From an identification of the individual regions which produced each of the 218 significant solar proton events, they found that 22% of the proton events were from solar regions that produced at least two or more discrete proton events.

C. Extremely Large Events

Occasionally solar and interplanetary conditions will combine to produce an unusually large proton event. These events have been called "Unusually Large" or "Anomalously Large" events; however, as shown by Feynman, et al. [5], they are at the high end of a log-normal distribution and should not be called anomalous.

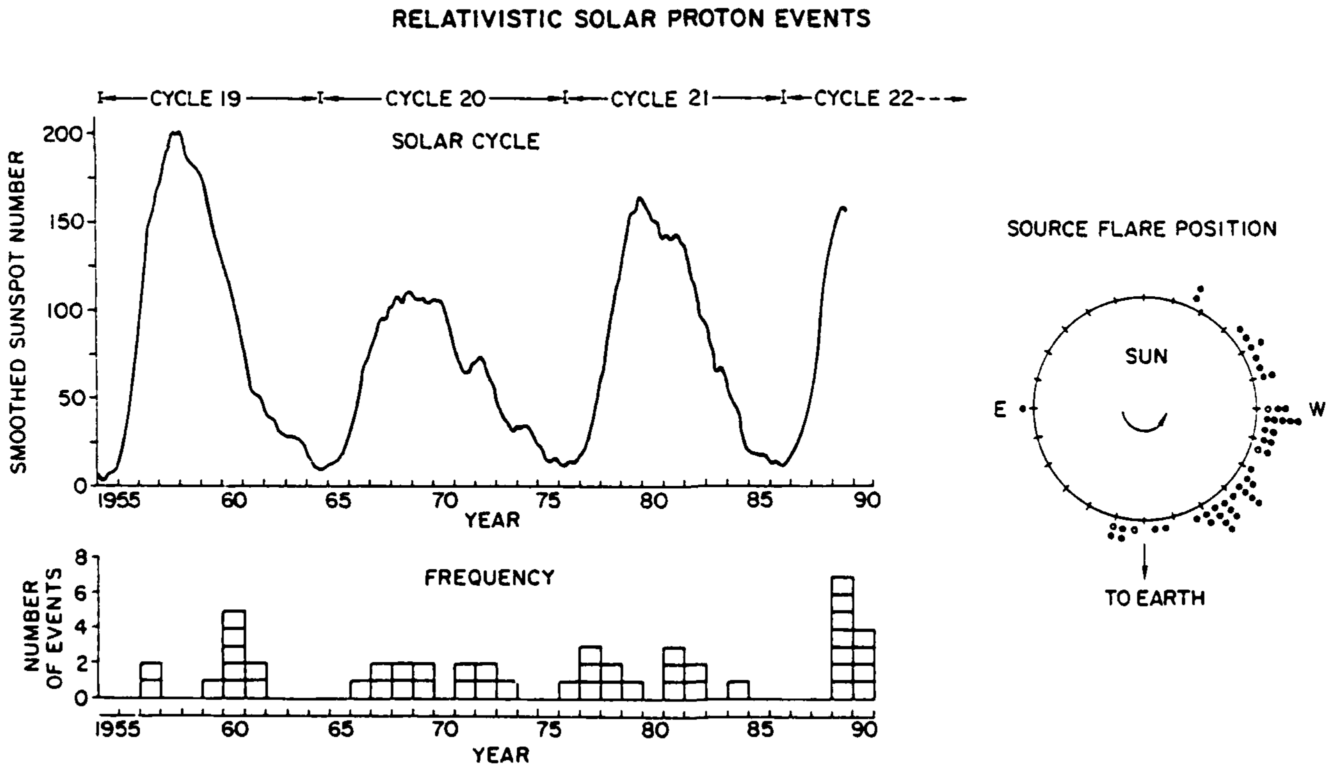

Figure 9. Frequency of relativistic solar proton events. (Bottom) The number of solar proton events containing relativistic solar protons (E > 450 MeV) each year between 1955 and 1991. (Top) The solar cycle as represented by the smoothed sunspot number for the past three solar cycles.

Figure 9. (Continued) Right side: The location on the solar disk of the flare assumed responsible for each of the relativistic solar proton events. Note that several of these flares are on the "invisible" side of the sun beyond the west limb.

These events typically occur when a series of major proton-producing flares (as described in the previous section) combine with one or more interplanetary shock waves in such a manner that the ambient particle flux is accelerated to energies considerably higher than the initial energy. Most of these large fluence events are also associated with great geomagnetic storms since a series of large flares, particularly near the central meridian of the sun (as viewed from the earth) often produce the interplanetary shock waves that are associated with geomagnetic storms at the earth. Examples of such events are those of July 1959, July 1961, and August 1972. The events of August 1972, with a particle fluence of 1.1 x 10^{10} protons/cm^2-sec, has often been used as a fiducial mark for a "worse case" solar proton fluence above 10 MeV, primarily because it was the first extremely large event for which we had comprehensive spacecraft measurements. However, there have been other events since August 1972 that had larger fluences at specific energies such as the major episode of activity in October 1989.

D. Relativistic Solar Proton Events

Cosmic ray neutron monitors provide the longest and most homogeneous set of solar proton data with information on the relativistic events that have occurred during the past three solar cycles. Protons having energies greater than approximately 450 MeV can be detected by neutron monitors in the earth's polar regions (above a geomagnetic latitude of ~ 60°). For detectors at mid and equatorial latitudes, the threshold energy is determined by the earth's magnetic field. Protons must have energies of approximately 15 GeV or greater to be detected in the vertical direction in the equatorial regions. Of the 218 solar proton events identified between 1954 and 1986, Shea and Smart [2] found that more than 15% of the events contained protons having sufficient energy (above 450 MeV) to be detected by neutron monitors. Figure 9 illustrates the occurrence of these relativistic solar proton events at the earth since 1955.

Most relativistic solar proton events are relatively short lived with the high energy particle flux passing the earth within a few hours. The higher the energy of particles present, the shorter the exposure time to particles having a specific energy. There is currently no way to predict the duration of relativistic solar proton events since the duration depends primarily on the rate at which the particles diffuse in the interplanetary medium, and this diffusion is dependent upon many factors. Figure 10 illustrates the duration of two comparable events as recorded by the neutron monitor located at sea level on Kerguelen Island in the Indian Ocean. The event on 7 May 1978 had the highest increase for all relativistic solar proton events in either the 20th or 21st solar cycles with a recorded increase of 214% for protons above 508 MeV (magnetic rigidity of 1.1 GV). The event had a duration of approximately two hours. The event on 29 September 1989 with its comparable increase lasted more than 20 hours. For unknown reasons, the events of this solar cycle have been of considerably longer duration than similar events of the previous two solar cycles.

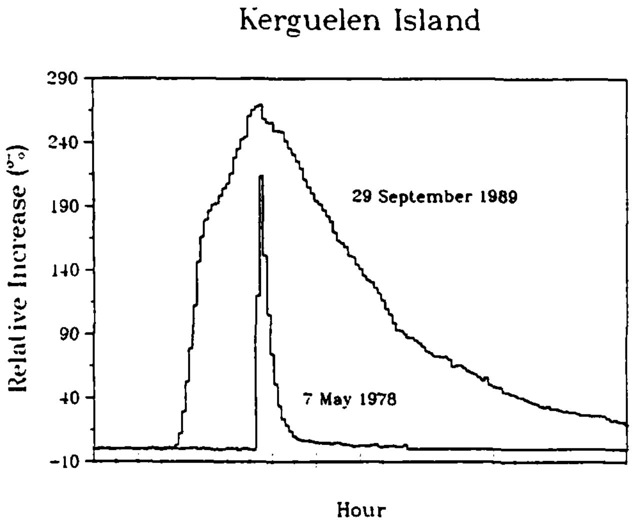

Figure 10. Duration of relativistic solar proton events.

E. Solar Proton Events During the 22nd Solar Cycle

There has been an unexpectedly large number of solar proton events during this 22nd solar cycle with over 70 "significant" events reported in the first five years of the cycle. The largest relativistic solar proton event since February 1956 occurred in September 1989; this event was followed by three more relativistic solar proton events within the next month. In addition to these high energy proton events, there have been several episodes of solar activity accompanied by major proton fluences and great geomagnetic storms. Table 1 gives the solar proton fluence greater than 10 and 30 MeV for the past three solar cycles. At the bottom of the table are the fluences for some of the major events of the present solar cycle as obtained from the GOES spacecraft (H. Sauer, private communication). As can be seen from this table, the fluence for solar protons with E > 10 and >30 MeV for this solar cycle, which is about halfway over, is larger than the solar proton fluence for either of the past two solar cycles. However, the 19th solar cycle still has the largest total solar proton fluence for the past three cycles.

IV. POTENTIAL THREAT OF SOLAR PROTON EVENTS

To understand the potential threat of solar proton events to missions in space, we have separated the problem into two major categories: spacecraft that orbit the earth at relatively low altitudes, and spacecraft that are beyond the influence of the magnetosphere (i.e., lunar and interplanetary missions).

A. Solar Proton Threat for Near-Earth Orbits

1. The Shielding Effect of the Geomagnetic Field. The earth's geomagnetic field effectively acts as a momentum analyzer and effectively reduces the amount of high energy particulate radiation that can reach the spacecraft depending upon the altitude and inclination of the spacecraft orbit. To understand the potential threat of solar protons to near-earth orbits, it is necessary to describe this shielding effect. The detection of a particle at any specific point in the magneto-

Table 1.

Summary of Solar Proton Events for Solar Cycles 19, 20, and 21

Cycle	Start*	End	No. of Months in Cycle	No. of Discrete Proton Events	No. of Discrete Proton Producing Regions	Solar Cycle Integrated Solar Proton Fluence > 10 MeV	Solar Cycle Integrated Solar Proton Fluence > 30 MeV
19	May 1954	Oct 1964	126	65	47	7.2×10^{10}	1.8×10^{10}
20	Nov 1964	Jun 1976	140	72	56	2.2×10^{10}	6.9×10^{9}
21	Jul 1976	Sep 1986	123	81	57	1.8×10^{10}	2.8×10^{9}
22	Mar 7-25, 1989					1.2×10^{9}	3.0×10^{7}
	Aug 12-18, 1989					7.6×10^{9}	1.4×10^{9}
	Sept 29 - Oct 2, 1989					3.8×10^{9}	1.4×10^{9}
	Oct 19-30, 1989					1.9×10^{10}	4.2×10^{9}
	Dec 30, 1989 - Jan 2, 1990					2.1×10^{9}	1.3×10^{8}
	May 21-24, 1990					1.2×10^{8}	4.0×10^{7}
	Mar 22-26, 1991					9.6×10^{9}	1.8×10^{9}
	Jun 03-18, 1991					2.6×10^{8}	
					Totals:	4.4×10^{10}	9.0×10^{9}

* The start of each solar cycle was selected as the month after the minimum in the smoothed sunspot number [6].

sphere is dependent upon the magnetic rigidity (i.e. momentum per unit charge) of the incoming particle, the geographic coordinates, altitude, and angle of incidence at the detection location, and the state (i.e. quiescent or disturbed) of the geomagnetic field. The minimum rigidity required to reach a point in the magnetosphere is called the lower cutoff rigidity; the effective cutoff rigidity allows for the transparency of the cosmic ray penumbra. Because of the complexities of the cosmic ray cutoff calculations, the commonly used reference value is the effective cutoff rigidity for the vertical direction [7].

Figure 11 shows the iso-rigidity contours of vertical cutoff rigidity as determined from a large number of calculations made around the world [8]. These high precision cutoff rigidity values were calculated using a 10th order quiescent geomagnetic field model appropriate for March 1980.0. The values given represent the rigidity, in GV, required for a particle to reach the top of the atmosphere at a specific location in the vertical direction. In other words all particles having higher rigidity can reach the spacecraft at that point in space. Because of the offset of the earth's dipole and higher order moments in the earth's magnetic field, the contour lines are not symmetric.

This iso-rigidity contour map was prepared from calculations for an altitude of 20 km which is roughly equivalent to the top of the atmosphere. As one increases in altitude the vertical cutoff rigidity decreases. Also, when the geomagnetic field is highly disturbed, such as during a major geomagnetic storm, the geomagnetic cutoff can be appreciably lowered in a predictable manner [9]; however, major geomagnetic storms usually persist for only a day or two.

An equivalent method of estimating the geomagnetic cutoff in a low altitude earth orbit is to utilize the approximation provided by the McIlwain [10] L-parameter. This quantity was originally used to bring order to trapped radiation data; however, its computation accounts for the higher order moments present in the earth's magnetic field. It has been shown [11,12] that the L-parameter has an excellent correlation with geomagnetic cutoff. The use of the L-parameter also accounts for variations in altitude [13] and changes observed in the geomagnetic field for the past 30 years. For practical applications, a satellite within the domain of L = 4 may be considered to be "shielded" from the interplanetary cosmic ray flux and a spacecraft beyond L = 4 may be considered to be "exposed" to the interplanetary flux. (The L = 4 position is equivalent to a corrected geomagnetic latitude of 60° and also a vertical cutoff rigidity of 1 GV.)

2. Low-Inclination Orbits. From Figure 11 it can be seen that particles must have a rigidity of at least 4 GV to reach a low altitude low inclination orbit of 30° in the vertical direction. This minimum rigidity value would be for an extremely limited portion of the spacecraft orbit over Florida. Incoming protons would require higher rigidities to reach other locations in this orbit. Over India, for example, particles would need a rigidity of > 17 GV to reach the spacecraft from the vertical direction.

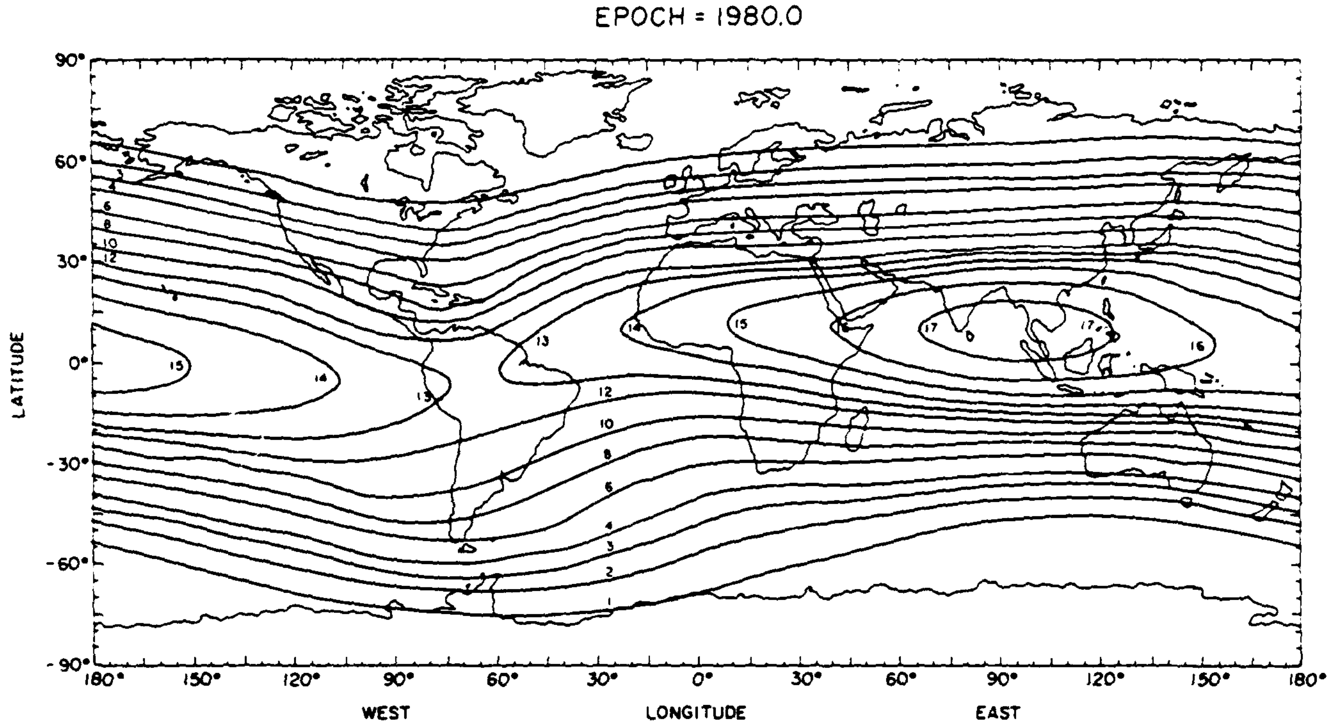

Figure 11. World map of iso-rigidity contours.

The threat of solar protons to this orbit is minimal. Only relativistic solar protons can penetrate to low altitude spacecraft having a 30° orbital inclination, and, as mentioned previously, these events are relatively rare and are usually short lived. The earth's geomagnetic shield is so effective that the intensity expected at low latitudes even during a "major" high energy solar proton event is of the same order of magnitude as the background cosmic radiation. However, each solar cycle there are one or two solar proton events having high energy particles that penetrate to equatorial latitudes, and mission planners should be cognizant of this fact.

3. High-Inclination Orbits. If the spacecraft is in a low altitude 60° inclination orbit, solar protons must have a rigidity above 1 GV to impact the spacecraft (except for a limited portion of the orbit over North America and south of Australia). Even for a major solar proton event such as occurred in September 1989, the geomagnetic shielding provides very effective protection to a 60° inclination orbit. Interplanetary radiation dose calculations by Lett et al. [14] based on solar proton measurements [15] indicate that the interplanetary radiation dose of 0.24 Gy to the blood forming organs of an astronaut shielded by 2 grams would have been debilitating. The actual dose measurements during this event on the MIR Space Station (orbital inclination of 51.6°) indicate that the cosmonauts experienced an actual dose of 0.525 rads (0.00525 Gy) [16]. Finally, if the spacecraft is in a polar orbit, it will be subjected to the full interplanetary flux at magnetic latitudes > 60°.

For 90° polar orbits a spacecraft spends approximately one third of its time above geographic latitudes of 60°. For the remainder of the orbit, the spacecraft traverses lower latitudes where the geomagnetic field effectively shields all but the most energetic protons. The greatest potential hazard for space operations in true polar orbits would be for extra-vehicular activities (EVA). EVA activities should be planned so that the astronaut could return to the spacecraft within the time period of one half orbit. Additional shielding precautions beyond about 5 grams of absorber are necessary only for the extremely large very high fluence energetic solar particle events.

B. Solar Proton Threat for Lunar Missions

Space missions to the moon will be subjected to the entire galactic cosmic radiation, which is relatively constant modulated by the solar cycle, and against which "light" shielding is ineffective. In addition the lunar surface will receive the full solar particle flux present in interplanetary space in the vicinity of the earth. Although the moon spends a portion of its orbit in the magnetospheric tail, the magnetic field in this region is insufficient to shield the lunar surface from solar protons. Methods developed to predict a solar proton event at the earth are applicable to predicting a solar proton event for a lunar mission. Major problems could arise with the extremely large solar proton event which cannot be predicted; however, lunar mission planners have the advantage that earth-based detectors can view the visible solar disk, and forecasters will be aware of potentially harmful regions that may be traversing the solar disk.

In addition to solar protons from flares that are visually observed, approximately 20% of the solar proton events detected at the earth have been associated with activity (presumably solar flares) from beyond the western limb of the sun and hence invisible from the earth. Unfortunately, there is no way to predict a reliable flux of solar protons from these flares. A solar flare from behind the west limb of the sun producing an unexpectedly large solar proton event, such as occurred on 16 February 1984 and 29 September 1989, could present a hazard for lunar exploration. The emergency reaction procedure should be to have access to an area shielded by a minimum of 15 grams of absorber within one hour.

C. Solar Proton Threat for an Interplanetary Mission to Mars

Space missions into the interplanetary medium to Mars, will also be subjected to the entire galactic cosmic radiation in addition to being vulnerable to all energies from solar proton events. The possible exposure to a very large solar proton event during a Mars missions should be viewed as an operational constraint which can be mitigated by proper contingency planning. Calculations by Wilson et al. [17] indicate that approximately 15 grams of shielding would have been necessary to reduce the radiation exposure to the blood forming organs from any of the three largest observed solar proton events to the 0.25 Sv 30-day limit. Again, our recommendation for an emergency reaction procedure would be that the astronauts have access to an area shielded by a minimum of 15 grams of absorber within one hour.

There is another limitation that must be considered in planning a mission to Mars, and that is our inability to view, from the earth, the possible flares that might impact the spacecraft for a significant portion of the orbit. As noted previously, the idealized "favorable propagation path" from the sun to the earth has a "footpoint" on the sun located at approximately 60° west heliolongitude (as viewed from the earth). As a spacecraft traverses the 0.5 AU distance beyond the earth's orbit, this "footpoint" will be at progressively larger distances from the spacecraft-sun line until, at the orbit of Mars the "footpoint" is located at approximately 90° west heliolongitude (as viewed from the Mars orbital distance). During the several month passage to and from Mars, it may not be possible for earth-based sensors to continuously monitor the sun for flares located near the "footpoint" for the spacecraft since the earth-based observations can only see one half of the sun. Clearly a manned interplanetary mission should have on-board capability of detecting major flares that would be potentially hazardous. In addition on-board particle sensors would be critical to determine if mitigating procedures are necessary.

An example of proton events impacting spacecraft from flares on the "invisible" portion of the sun, is the event observed on 8 and 9 August 1970. During this event the entire inner heliosphere was populated by energetic particles [2] as shown in Figure 12. In this figure the relative solar proton intensity (on a log scale) as measured by the Pioneers 8 and 9 space probes and the earth-orbiting IMP 5 is represented by the bars placed at the location of the indicated spacecraft. Pioneer 9 observed the largest maximum increase on 8 August, and Pioneer 8 had a smaller increase with maximum intensity on 9 August. A possible flare located approximately 40° behind the east limb was assumed to be the source of this particle event. The small increase observed on IMP 5 is consistent with this flare location. The Pioneer measurements were for particles above 14 MeV; the IMP measurements were for particles above 10 MeV. Had an interplanetary mission been at the location of the Pioneer 9 space probe, the spacecraft would have been subjected to a major proton event which would not have been anticipated by any earth-based measurements.

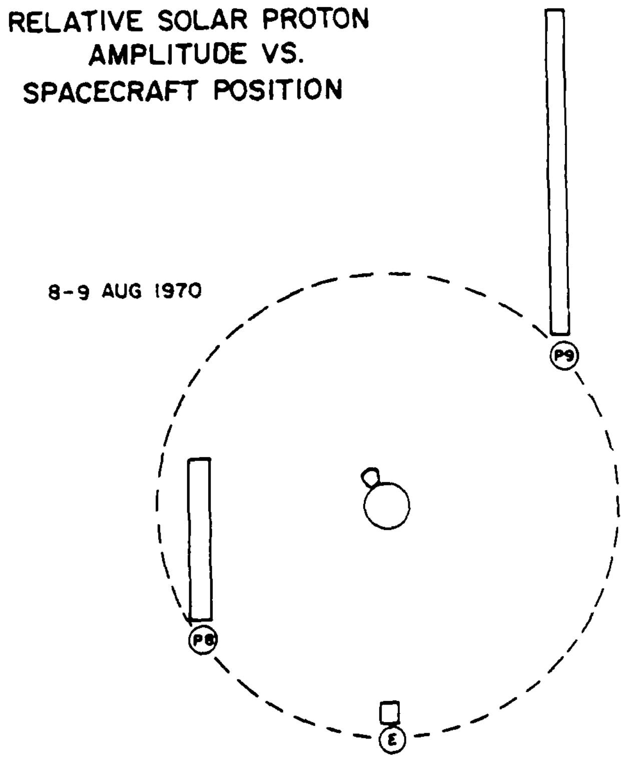

Figure 12. Relative solar particle intensity (on a log scale) as measured on Pioneer 9, Pioneer 8 and IMP 5 (at the earth) for the particle event of 8-9 August 1970. The bars representing the particle flux are placed at the location of the indicted spacecraft. This event has been attributed to a solar flare approximately 40° behind the east limb of the sun. The Pioneer measurements were for particles above 14 MeV; the IMP measurements were for particles above 10 MeV.

V. SUMMARY

Solar particle events can occur at any time in the solar cycle. They come in various sizes and with different intensity-time profiles usually dependent upon the location of the flare with respect to the detection site and the characteristics of the interplanetary medium at the time of the event. There is no guarantee that specific events will or will not occur during a projected mission time frame. The only guidelines that can be given will be generated from statistical studies of ground-based and spacecraft measurements conducted over the past solar cycles.

In considering the potential threat of solar protons to various space missions, the following guidance should be considered:

(1) Relativistic solar protons are the only solar protons that can penetrate the geomagnetic field to low inclination orbits in near-earth space. These events are comparatively rare and are usually short-lived; however, one should be cognizant of the fact that extremely large relativistic solar proton events have occurred in the past and will undoubtedly occur in the future.

(2) Spacecraft in high inclination and/or polar orbits would be subjected to the full flux of a solar particle event while in the high latitudes. However, each orbit traverses the equatorial regions where lower energy particles cannot penetrate thereby considerably mitigating the potential threat.

(3) On a lunar or interplanetary mission, beyond the protection of the geomagnetic shield, the spacecraft could be subjected to the full fluence of each solar proton event. Although the magnitude of each event would be a function of the heliolongitude of the solar flare with respect to the spacecraft position, spacecraft planners would be well advised to consider using both on-board sensors to determine the severity of each event and also consider re-positioning the material in the spacecraft so that maximum shielding could surround the occupants.

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